Theme 1: High-Resolution Global Models

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with many thanks to
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Terminology

The term "high-resolution" is being used rather loosely … we are seeking models that accurately represent the dynamics and physics of storms (extra-tropical and tropical) in the atmosphere, eddies in the ocean, and catchment flows on the land surface, as well as all phenomena at scales larger than these.

Theme 1 Questions

1. How does prediction skill and fidelity change when resolution is increased in combination for the various components of the prediction system?
2. How can we diagnose and address model behaviors that lead to the sensitivity?
3. Are there specific or related processes in the coupled system that drive prediction error in the short-term forecast and climate simulation bias?
4. What resolutions are necessary to adequately resolve these processes?

We also asked Team 1 participants to answer this:

With respect to each of the questions above, what are the “Prospects for Advancement” and what are the “Issues and Challenges”?

Theme 1 Questions

1. How does prediction skill and fidelity change when resolution is increased in combination for the various components of the prediction system?
   - There are many examples where mesoscale features (ex: tropical cyclones, convective clusters) improve with resolution in current AGCMs, e.g., orographic precip; tropical cyclones and mesoscale complexes in midlatitudes; tropical Atlantic thermocline slope
   - HOWEVER: Processes dominated by scale-sensitive parameterizations can show degraded skill as resolution is increased, e.g., clouds deteriorate, double ITCZ strengthens; biases set in faster
   - Some complex phenomena like MJO and ENSO are unchanged

Theme 1 Questions

2. How can we diagnose and address model behaviors that lead to the sensitivity?
    - Short range prediction (1-2 months) with DA and analysis increments to understand evolution of COUPLED errors and loss of coherent phenomena like MJO. High frequencies can be analyzed in the same fashion
    - Cross-pollinate across models and DA methods; tightly coordinate across groups

Theme 1 Questions

3. Are there specific or related processes in the coupled system that drive prediction error in the short-term forecast and climate simulation bias?
   - Vertical structure of moist processes in the PBL and deep convection; the difficulty is that the climatic state is a prime determiner of this structure so the problem is lack of system maintenance; moist processes that force a climate that coerce the model to stay close nature and to the states for which the vertical structure of heating and moistening result in convective organization and representative ocean forcing

Theme 1 Questions

4. What resolutions are necessary to adequately resolve these processes?
   - ECMWF & COLA: AGCM @ Δx = 30-50 km
   - NCAR: AGCM @ $\Delta x \leq 25$ km for horizontal grid length
   - NICAM @ < 7 km to reproduce small high clouds (Radius<50km) that cause large future changes in CRF under a warmer climate (Noda et al. 2014).
   - Max. grid spacing for convection-permitting models 4 km (Prein et al. 2014).
   - NICAM @ $\Delta x < 2$ km to resolve a convective core (Miyamoto et al. 2013).
   - NICAM @ $\Delta z < 0.4$ km to resolve cirrus clouds (Seiki et al. 2015).
   - Met Office & ECMWF: OGCM @ $\Delta x \leq 25$ km
   - NCAR: OGCM @ $\Delta x \leq 0.1°$ (eddy-resolving)

Theme 1 Questions

With respect to each of these questions, what are the

"Prospects for Advancement"

and what are the

"Issues and Challenges"?

Theme 1 Prospects for Advancement

- *Consensus.* Resolving mesoscale in atmosphere and ocean may lead to improved simulations of mean climate, variability, small-scale features and extremes.
- *Proof of concept.* Recent success using global coupled models with near-mesoscale horizontal resolution in the ocean and atmosphere (e.g., Bryan et al. 2010; Kirtman et al. 2012; Kinter et al. 2013; Small et al. 2014). Higher vertical resolution in the stratosphere leads to a better simulation of troposphere-stratosphere interactions.
- *Buy-in*. The awareness in the community is clearly growing (e.g. GFDL and NCAR).
- *Priorities and tradeoffs*.
  - Are human and computing resources better spent on new dynamical cores or on increasing the resolution and retuning?
  - Should we be using very high-resolution atmosphere-only models or fully coupled not-so-high-resolution models for sub-seasonal prediction?
  - Multi-resolution global models allow for computationally "cheaper" assessment of regional model performance at high-resolution; however, there may be large performance differences depending on how the grid is handled (e.g. stretching vs. nesting)

NB: Prospects are contingent on availability of required computing resources.

Theme 1 Challenges and Issues

- Critical resolution requirements dominated by process of interest (1)
  - Why is there an apparent step function in performance with global atmospheric resolution at ~35-50-km grid spacing (Minerva; GFDL). Is it the topography? Why do we realize only minor further gains with grid spacing between 35 and 10 km? There is a similar step function in ocean resolution (eddy-permitting vs. eddy-resolving).
  - Effective resolution, and therefore parameterization development, depends critically on the dynamical core. A 50-km grid spacing produces different results in models having different levels of accuracy in the core differencing scheme..
  - Do we need to increase the vertical resolution in the atmosphere, e.g., to improve the simulation of gravity-wave breaking and ozone variability? Are we over-smoothing orography? Can we ever stop parameterizing mountain drag?
  - Do we need higher vertical resolution in the ocean? Should ocean & atmosphere grids match?

Theme 1 Challenges and Issues

- Critical resolution requirements dominated by process of interest (2)
  - Convection must be parameterized in current global atmospheric models
  - There are "gray zones" in model resolution space: Grid spacing between 10 km and 4 km is a "gray zone" in climate models (Prein et al. 2014), where some assumptions in the conventional parameterizations of deep convection are violated, and deep convection is not sufficiently resolved to be modeled explicitly. The gray zone in cloud-PBL models is ~1 km, below which turbulence (actually very large eddy) is partially resolved. There is not much to be gained merely by increasing resolution until past the gray zones. Hence, convection must be (super?) parameterized in global atmospheric models for the foreseeable future.
  - High horizontal resolution in the ocean (particularly near the western boundary currents), and high vertical ocean resolution in the mixed layer and below is critical to getting air-sea interactions correct.

Theme 1 Challenges and Issues

- Critical resolution requirements dominated by process of interest (3)
  - Increased resolution of land alone doesn't necessarily affect prediction skill.

    BUT …

  - Better resolving subgrid variability, which *if translated to subgrid fluxes to subgrid (unresolved) atmospheric processes* might have a climate impact. This is particularly true where processes are not linear (i.e., where there is a rectified effect of subgrid variations), e.g., anything that crosses a phase change of water (surface freezing, cloud formation) over a part of a grid.
  - Better resolving climate effects upon land is critical for applications and impacts assessment, say, at catchment scales.

Theme 1 Challenges and Issues

- *Parameterization*:
  - Overhaul of parameterizations at higher resolution needed → "scale-aware" parameterizations?
  - Which processes now parameterized will be explicitly modeled, and which processes (e.g. gravity waves, turbulence) will continue to be parameterized? Is super-parameterization viable as an approach?
  - Increasing resolution should be done in conjunction with improving representation of sub-grid scale processes such as convection, turbulence, and component interactions; how does this affect multi-resolution model development?
  - Diurnal cycle (phase and amplitude) over continents – Better fast physics required?
  - We are not representing coupled land-atmosphere processes well. https://www.dropbox.com/s/dthrhpr3e1pnax9/Coupling_metrics_V2.1.docx?dl=0
  - Station measurements may be quite different from area averages (analogous to model grid boxes), which means there are scale-dependent statistics that imply resolution-dependence.

Resource: Seminars on "physics" at ECMWF: http://www.ecmwf.int/en/annual-seminar-2015.

Theme 1 Challenges and Issues

- *Initialization and verification for predictions:*
  - Observational networks are not up to global mesoscale, especially for land surface, sub-surface ocean, sea ice. Current practices in data assimilation not necessarily appropriate for mesoscale.
- *Long runs*.
  - Very long runs (>100 years, particularly for deep ocean) are needed for climate simulations (e.g. equilibrium climate sensitivity), which in practice are hard to implement due to computational requirements (serial runs, large allocations).
- *Bias*.
  - Resolution is not necessarily the solution to long-standing coupled model biases. How will we address model biases that seem unaffected by resolution changes?
- *Diagnostics*.
  - Considerable diagnostic work is needed to determine if high resolution models can capture the observed mesoscale organized structures (e.g. cloud clusters, lines of thunderstorms, squall lines), and if not why not. (and if so, does it matter for climate?)

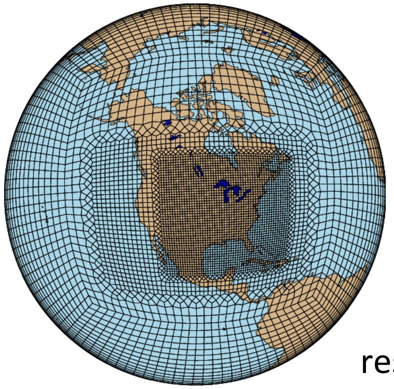
Theme 1 Challenges and Issues

- *IT issues*:
  - The requirements for HPC and data storage are beyond current capabilities. We need smart methodologies to store high resolution data from model output. Given finite computing resources, do we gain more by increasing resolution or running bigger ensembles? E.g., seasonal climate predictions and climate change projections are typically over-confident.
- *Institutional*.
  - For decadal predictions and climate change projections, major institutions don't want to commit to use mesoscale-resolving global models → seamless paradigm is harder to achieve.
- *Regional information*.
  - Push for high resolution is (partially) driven by need for regional information. Do we know whether global high resolution is best for the needed predictions? Does it depend on the target? Is there a role for regional modeling or is it only an intermediate step until the global models reach the next level of resolution?

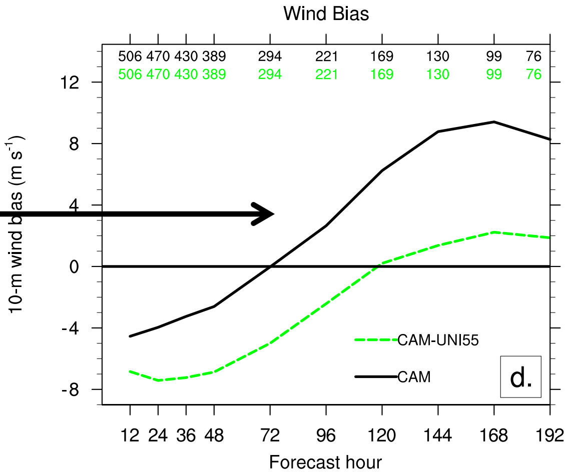
INDIVIDUAL CONTRIBUTIONS

Mesoscale Features in Global Models

- Prospects for advancement
  - Multi-resolution global models allow for computationally "cheaper" assessment of regional model performance at high-resolution
    - Direct improvement in model results through increased resolution given computing availability
    - Platform for testing/development of new parameterizations, etc.
- Issues and challenges
  - Many examples where mesoscale features (ex: tropical cyclones, convective clusters) improve with resolution in current AGCMs
  - Processes dominated by scale-sensitive parameterizations can show degraded skill as resolution is increased
  - Critical resolution requirements dominated by process of interest, particularly at <10 km grid spacing



Multi-resolution CAM-SE grid



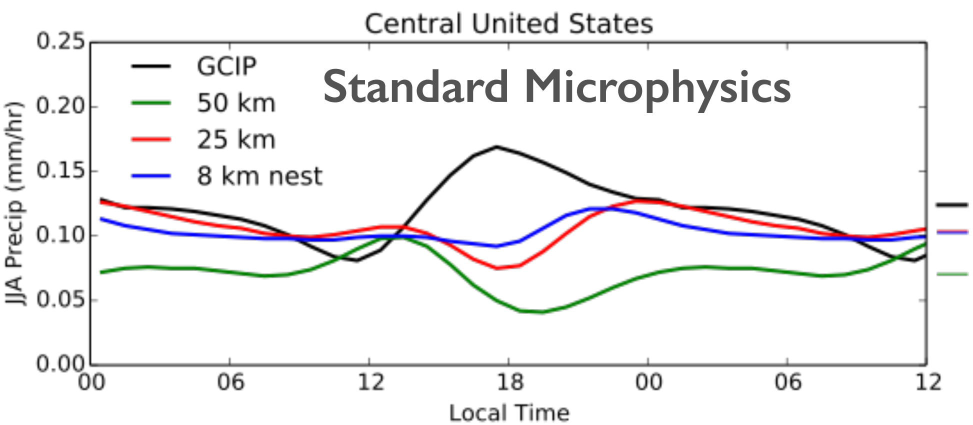
CAM-SE 2012-2013 tropical cyclone forecast wind error as function of lead time for identically-initialized 55km (green) and 14km (black) model grids. Note how high bias in intensity (beyond 120 hours) exacerbated in 14km model (potentially giving less skillful intensity forecasts). From Zarzycki and Jablonowski, MWR, 2015.

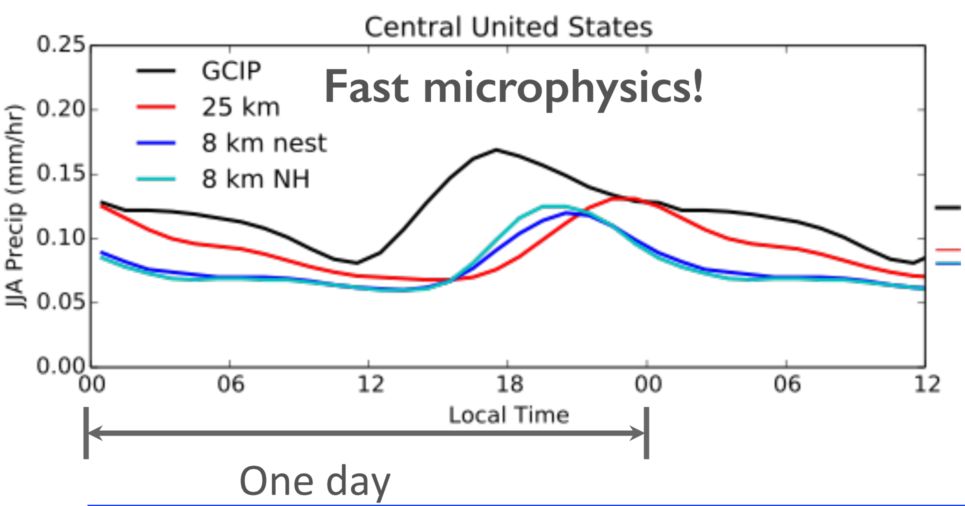
Courtesy of Colin Zarzycki

- Prospects for Advancement
  - Atmospheric models with resolution of 30~50 km show improved statistics and predictability for extra-tropical flow regimes w.r.t typical resolutions currently used for seasonal predictions. Such a resolution is computationally feasible for the next generation of S2S forecast systems.
  - Use of eddy-permitting ocean models are expected to improve the simulation of ocean-atmosphere interactions in the region of western boundary currents.
  - Higher vertical resolution in the stratosphere leads to a better simulation of troposphere-stratosphere interactions.
- Issues and Challenges
  - Organized convection in the warm pool region still suffers from biases in amplitude and propagation speed: do we need higher resolution, better convection schemes or better specification of heat/moisture fluxes over maritime continents and seas with shallow mixed layer?
  - In the stratosphere, we need to improve the simulation of gravity-wave breaking and ozone variability in addition to resolution.
  - Ocean-atmosphere feedbacks affecting tropical cyclones need to be properly represented in high-res. models (which are no longer under-active)
  - Initialization of sea-ice models in re-forecasts suffers from scarcity of observations on ice thickness (and other physical properties) during the last decades.

Courtesy of Franco Molteni

High-resolution global models: nesting and microphysics





Most global models have severe errors in their continental warm-season diurnal cycles. GFDL HiRAM is no exception.

Increasing resolution to 8 km by nesting removes the noontime bias of lower-resolution models but still doesn't capture the amplitude of the observed (GCIP) cycle.

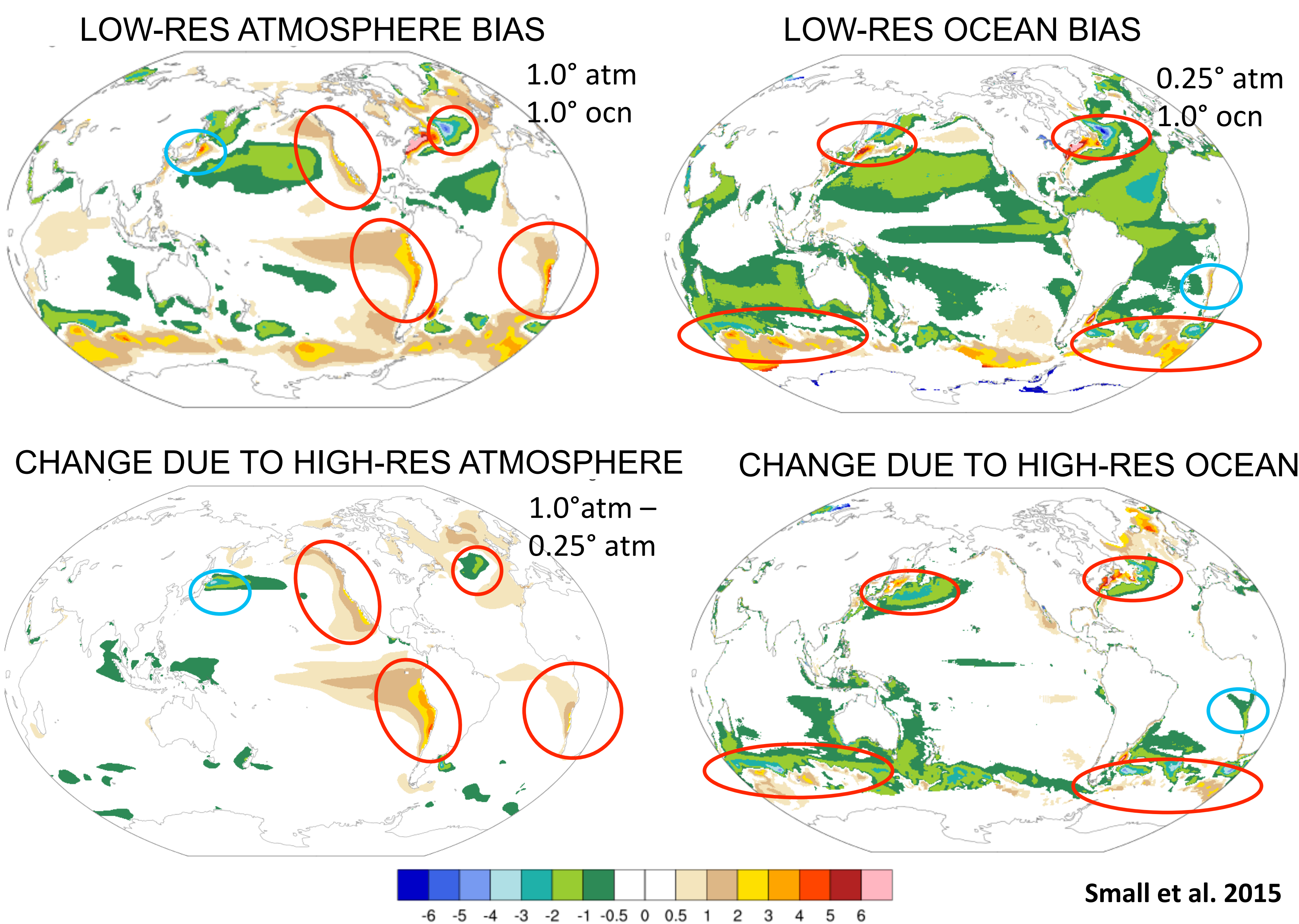
New microphysics sub-cycles latent heating and precipitation fall, circumventing the convection scheme. Diurnal cycle greatly improved!

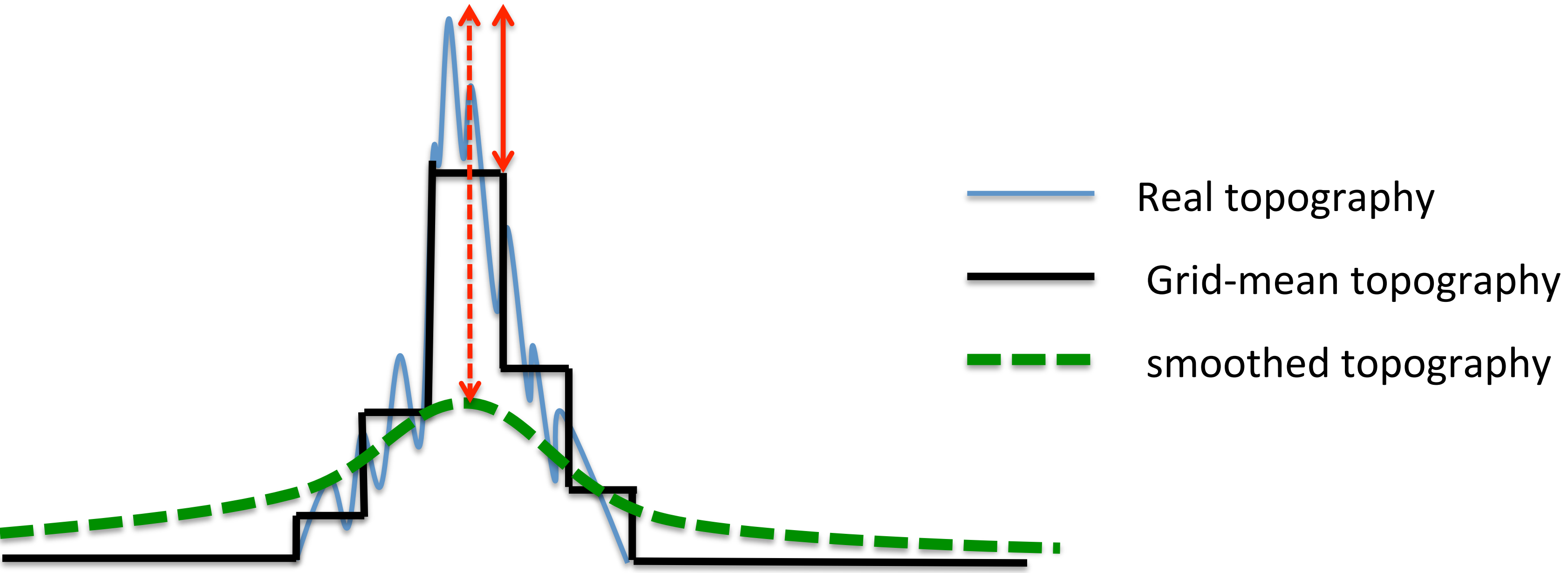
Courtesy of Lucas Harris

Perspectives from CESM High-Res Coupled Climate Experiments

- **Prospects for advancement w/ higher resolution**
  - Western boundary current separation and position
  - Atmos. boundary layer response to SST fronts (Chelton and Xie 2010; Bryan et al. 2010)
  - Eastern boundary near-shore winds and upwelling response (Small et al. 2015 – *see attached figure*)
  - Ocean eddy-driven heat content variability and associated atmospheric response (Dong et al. 2004; Kirtman et al. 2012; Bishop et a.l 2015)
- **Issues and Challenges**
  - Subgrid-scale closure for ocean eddy-resolving regime (Fox-Kemper and Menemenlis 2008)
  - Paucity of global high-resolution subsurface ocean observations
  - Very limited experience with fully coupled high-resolution models

Courtesy of Frank Bryan


LOW-RES ATMOSPHERE BIAS
1.0° atm
1.0° ocn
LOW-RES OCEAN BIAS
0.25° atm
1.0° ocn
CHANGE DUE TO HIGH-RES ATMOSPHERE
1.0°atm –
0.25° atm
CHANGE DUE TO HIGH-RES OCEAN
-6 -5 -4 -3 -2 -1 -0.5 0 0.5 1 2 3 4 5 6
Small et al. 2015



Issues/Challenges

- Topographic precipitation biases
  - Implicit/explicit smoothing on σ-surfaces?
  - Bad pressure force numerics?
- Most models smooth topography. Unclear what should be parameterized, e.g.: Figure above – dashed arrow or solid arrow?
- When can we drop orographic drag parameterizations -10km, 5km ..never?

Prospects for advancement

- Diffusion on Z
- Better/new parameterization of orographic drag
- Z-coordinates instead of σ

Courtesy of Julio Bacmeister

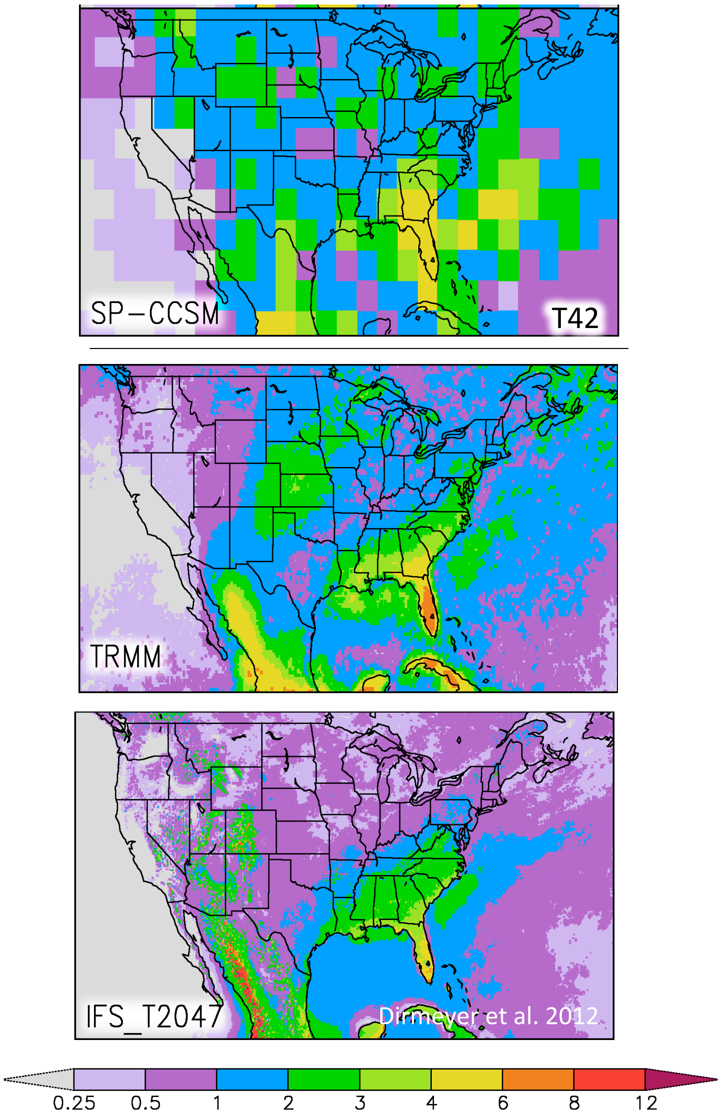
Prospects for advancement

The increase in resolution should be done in conjunction with the improvement in the representation of sub-grid scale processes such as convection, turbulence, and interactions between the components of the prediction system.

Issues and Challenges

Hohenegger et al. 2009 showed that in the Alpine region the positive soil-moisture precipitation feedback simulated by a low-resolution, parameterized convection model became negative in the high-resolution, resolved convection version of the model.

Amplitude of the diurnal cycle



Dirmeyer et al., 2012 found that increasing resolution alone has little impact on the timing of daily rainfall in IFS with parameterized convection, yet the amplitude of the diurnal cycle does improve along with the representation of mean rainfall. Introduction of an embedded cloud model within the NCAR model significantly improves global statistics of the seasonal mean and diurnal cycle of rainfall, as well as many regional features.

Taylor et al. 2013 also found that low-resolution models with parameterized convection tend to erroneously simulate a positive feedback between soil moisture and precipitation. Increasing the resolution alone did not have an impact on the simulation of land-atmosphere interactions.

Courtesy of Cristiana Stan

Threshold Resolution?

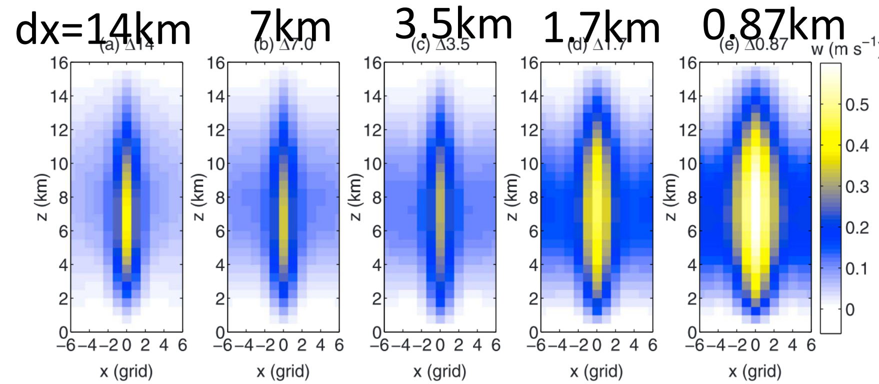
- We know that for the atmosphere there is a big difference in resolutions above and below ~50km. We found that in Athena, and GFDL picked the FLOR resolution based on the same findings in their model. ECMWF's study implicated topography as the critical difference. However, we have no idea what the key difference actually is. What are we getting at 50km that we are not getting at 100km? Why is there so little improvement beyond that? Do the other components need to increase resolution as well (see below)?

- We also know that 0.1 degree in the ocean has a huge impact on the simulation. The 640 million core hour question is what happens when we have comparable resolutions in both the atmosphere and the ocean. Since we are seeing step-function in the simulation when the individual components reach high resolution what happens when they all do?

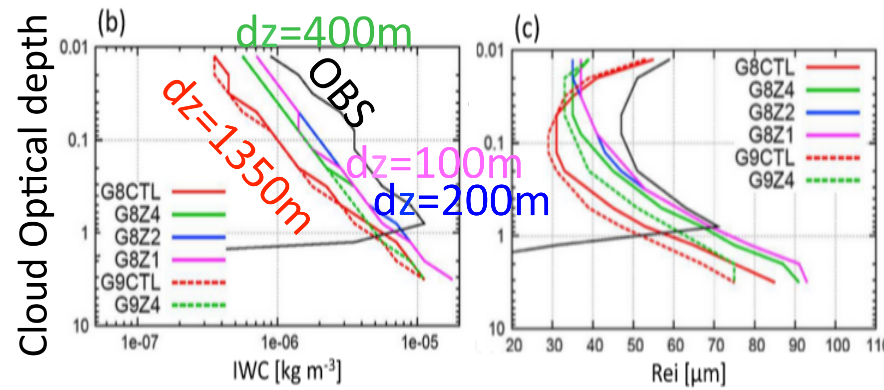
Courtesy of Ben Cash

Recent topics from NICAM

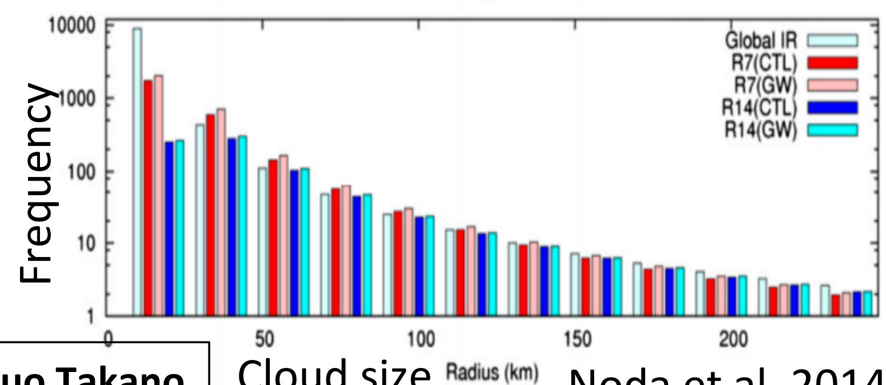
- Intraseasonal Oscillation
  - NICAM-14km shows a good skill for simulating ISO in extended-range timescale (Miyakawa et al. 2014; Nakano et al. 2015) and climate timescale (Kodama et al. 2015)
- Tropical Cyclones
  - NICAM-14km model can capture TC genesis 2 weeks in advance (Nakano et al. 2015)
  - NICAM-14km enables to examine future changes in characteristics of inner core region. (Yamada et al. 2015 in prep.)
- Clouds
  - Dx<2km is needed to resolve a convective core (Miyamoto et al. 2013).
  - Dz<400m is needed to resolve cirrus clouds (Seiki et al. 2015).
  - Dx<7km is needed to reproduce small high clouds (Radius<50km) that cause large future changes in CRF under a warmer climate (Noda et al. 2014).



Composites of w in convective clouds
Miyamoto et al. 2013



Seiki et al. 2015



Noda et al. 2014

Courtesy of Masuo Takano

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